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SEARCH FOR AN EXCESS OF EVENTS IN THE SUPER-KAMIOKANDE DETECTOR IN THE DIRECTIONS OF THE ASTROPHYSICAL NEUTRINOS REPORTED BY THE ICECUBE COLLABORATION

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ABSTRACT

We present the results of a search in the Super-Kamiokande (SK) detector for excesses of neutrinos with energies above a few GeV that are in the direction of the track events reported in IceCube. Data from all SK phases (SK-I through SK-IV) were used, spanning a period from April 1996 to April 2016 and corresponding to an exposure of 225 kilotonne-years . We considered the 14 IceCube track events from a data set with 1347 livetime days taken from 2010 to 2014. We use Poisson counting to determine if there is an excess of neutrinos detected in SK in a 10 degree search cone (5 degrees for the highest energy data set) around the reconstructed direction of the IceCube event. No significant excess was found in any of the search directions we examined. We also looked for coincidences with a recently reported IceCube multiplet event. No events were detected within a ± 500 s time window around the first detected event, and no significant excess was seen from that direction over the lifetime of SK.

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1. INTRODUCTION

Neutrino astronomy is a burgeoning field, bridging the gap between astronomy and particle physics. Neutrinos travel undistorted from their source, and are therefore a valuable probe of the inner workings of astrophysical phenomena. The first definitive measurement of high energy extragalactic neutrinos was made by the IceCube experiment in 2013 (IceCube Collaboration 2013), where they were able to reject the atmospheric-neutrino-only hypothesis at greater than 4 σ.

Detecting neutrinos that are astrophysical in origin has raised many questions: Where are these neutrinos coming from? What process is creating them? There has not yet been any significant evidence to suggest that these neutrinos are pointing to a particular region of the sky. The many searches for counterparts to the neutrino signal have been largely unsuccessful, including searches for coincidences with photons from Fermi LAT (Peng & Wang 2017), fast radio bursts (Fahey et al. 2016), as well as a search for coincidences with a large catalogue of candidate sources (Aartsen et al. 2017). One search (Kadler et al. 2016) found a coincidence between a PeV neutrino detected in IceCube and an outburst of the blazar PKS B1424418, giving a hint at a possible origin of these astrophysical neutrinos.

IceCube uses detected events with energies above a few hundred TeV to look for astrophysical neutrinos. In this energy region, the atmospheric neutrino background is expected to be low. However, now that astrophysical neutrino candidates have been identified, one can search in the lower energy data for an excess of events coming from the same direction. Given the unknown origin of these neutrinos, searching this previously unexplored energy region is of interest.

Super-Kamiokande (SK), a water Cherenkov detector located in Japan, detects atmospheric neutrinos in the energy range of 30 MeV to several TeV. For events with energies above a few GeV, the direction of the incoming neutrino can be reconstructed as it is well correlated with the direction of the detected outgoing lepton.

SK has performed a number of astrophysical neutrino searches in the past. Recent searches include a general, all-sky astrophysical search (Thrane et al. 2009b; Abe et al. 2006; Swanson et al. 2006), searches for coincidences with gamma ray bursts, supernova remnants, and other potential sources of astrophysical neutrinos (Thrane et al. 2009a; Desai et al. 2006; Thrane et al. 2009b), dark matter searches (Tanaka et al. 2011; Choi et al. 2011), and a search for coincidences with the recent detection of gravitational wave signals (Abe et al. 2016).

In this paper, we look for excesses of neutrino events in Super-Kamiokande in the direction of the IceCube events from their data release in IceCube Collaboration (2015). We use the IceCube events that have the best pointing accuracy, known as track events, and determine if there is an excess of events in the full SK high energy dataset. Given the uncertainty about the origins of these astrophysical neutrinos, we perform a model-blind search, without assuming an energy spectrum a priori. Since we have no observational or theoretical motivation for the time duration over which these neutrinos are emitted, we do not require any timing correlation between the IceCube and SK events. For this simple estimate, we omit discussions of systematic errors. We also report the search for coincidences with the recent multiplet event reported in Aartsen et al. (2017).

2. THE SUPER-KAMIOKANDE EXPERIMENT

The SK detector is a 50-kilotonne (22.5 kilotonne fiducial) water Cherenkov detector located in the Mozumi mine in the Gifu prefecture of Japan. The cylindrical detector is optically separated into an inner detector (ID) volume, which is viewed by $\sim$ 11,000 photomultiplier tubes (PMTs), and an outer detector (OD) volume, which is viewed by $\sim$ 2,000 PMTs. A more detailed description of the SK detector can be found in Fukuda et al. (2003).

The SK data is divided into four experimental phases. SKI ran from 1996-2001 with 40% photocoverage. In 2001, there was an accidental implosion that damaged some of the PMTs. SKII ran from 2002-2005 with a photocoverage of 20 %. In 2006, the damaged phototubes were repaired and the SKIII phase began with 40% photocoverage. After an electronics upgrade in 2008, the current phase of the experiment, SKIV, began. Data from all four phases of the experiment are used in this analysis, spanning April 1996 - April 2016 and corresponding to 225 kilotonne-years.

Detected neutrino events at energies above 30 MeV can have three different topologies in the SK detector. The first, known as fully-contained (FC) events, have a reconstructed vertex inside the fiducial volume, with little light seen in the OD. Events that have a reconstructed vertex inside the fiducial volume, but have interaction products that produce light in the OD, are known as partially-contained (PC) events. Finally, muon neutrinos that interact in the surrounding rock and produce penetrating muons are known as upward-going muon (UPMU) events. We require these events to be coming from below the horizon in order to distinguish them from cosmic muons. These topologies roughly represent increasing, though overlapping, energy regions. For the atmospheric neutrino energy spectrum, FC events have an average energy of about 1 GeV, PC events have an average energy of about 10 GeV, and UPMU events have an average energy of about 100 GeV. More information on the SK topologies, including the selection cuts used in the data reduction, can be found in (Ashie et al. 2005).

3. SEARCH METHOD

The IceCube search directions were taken from the October 2015 data release (IceCube Collaboration 2015). Only IceCube track events, which are mainly from ν_μ charged-current interactions, were used in this analysis. These events have a median angular resolution of better than 1°, allowing us to perform a spatial coincident search. Table 3 lists the properties of the IceCube events.

Event Number	Declination (degrees)	RA (degrees)	Deposited Energy (TeV)
1	-31.2	127.9	78.7
2	-0.4	110.6	71.4
3	-21.2	182.4	32.6
4	40.3	67.9	252.7
5	-24.8	345.6	31.5
6	-13.2	208.7	82.2
7	-71.5	164.8	46.1
8	20.7	167.3	30.8
9	14.0	93.3	200.5
10	-22.0	206.6	46.5
11	0.0	336.7	84.6
12	-86.3	219.0	429.9
13	67.4	209.4	74.3
14	-37.7	239.0	27.6

Table 1. Information on the track events from IceCube used in this coincidence search. The data were taken from IceCube Collaboration (2015).

To ensure that the detected lepton points back to the incoming neutrino, a low energy threshold was imposed on the FC and PC datasets. A minimum energy requirement was determined by calculating the lowest energy such that 50% of the reconstructed lepton directions of that energy agreed to within 10° of the incoming neutrino direction in the simulated data set from our Monte Carlo (MC) code. This threshold was determined to be 3.8 GeV for FC events and 2.1 GeV for PC events. No explicit upper energy cut was applied.

A search cone, centered at the reconstructed direction of each IceCube event, was defined with a half-angle opening of 10° for FC and PC events and 5° for UPMU events. The UPMU events are higher in energy than the other topologies and therefore the detected lepton points back to the incoming neutrino with more accuracy, allowing for a smaller search cone.

In this analysis, only basic selection cuts were applied post-reduction. For the FC data set, the cuts ensured that the reconstructed event vertex was more than 2.0 m from the detector wall, that the visible energy in the detector was greater than 3.8 GeV, and that there were fewer than 16 hits (10 for SK-I) in the outer detector volume. For the PC data set, the cuts ensured that the reconstructed event vertex was more than 2.0 m from the detector wall, that the visible energy in the detector was greater than 2.1 GeV, and that there was greater than or equal to 16 hits (10 for SK-I) in the outer detector volume. Finally, the UPMU data selection cuts ensured that the fit direction was below the horizon, that the fit track length was greater than 7.0 m for the events that the fitter classified as passing through the detector, and that the fitted momentum of the lepton was greater than 1.6 GeV for events that the fitter classified as stopping in the detector.

To determine if there is an excess of events coming from the direction of the high energy IceCube track events, Poisson statistics were used. A test statistic was constructed based on the maximum likelihood method. The likelihood of seeing N events in our search cone given the expected number of background events including oscillations (N_B) is,

$$L = \frac{e^{\frac{-N_B}{(1-\alpha)}}}{N!}\left(\frac{N_B}{1-\alpha}\right)^N , \tag{1}$$

where α represents the fraction of the N events that are from signal and is the parameter over which we maximize.

The background to this search is from atmospheric neutrinos. The SK MC code, along with a scaling for neutrino oscillations and the overall normalization of the flux, was used to determine the number of background events (N_B) we expect to see in our search cone. The MC code used Geant3 (Brun et al. 1987) to simulate particle interactions and tracking. We used 500 years of simulated atmospheric neutrino events for each SK phase. The truth information was generated using nuclear interaction models used in NEUT (Hayato 2009). We scaled the MC sample for each phase to the appropriate livetime, and then summed them together. Events were assigned right ascensions assuming a flat local sidereal time, and so the resulting N_B was assumed to depend only on declination. The combined sample was then scaled on an event-by-event basis to the all-sky, best-fit value from data, which accounts for the flux normalization and oscillations.

Our test statistic, Λ, is then,

$$\Lambda = 2\log\frac{L(\alpha_{\rm fitted})}{L(\alpha=0)}, \tag{2}$$

where $\alpha_{\rm fitted}$ is obtained from maximizing Equation 1. This is the final indicator of the statistical significance for the number of measured neutrino events in our search cone.

4. RESULTS

Figure 1 shows the spatial distribution of the detected neutrino events in the region of each search direction. The density of the events are dependent on declination. This can be seen most clearly in the UPMU data sample, where there is a high density near the southern pole and no events at declinations above 54° (see event 13 in Figure 1). The density of detected neutrino events does not appear to be significantly higher inside any of the search regions compared with the density around the search regions.

Figure 2 shows the background expectations for the three topologies considered in this search. The background expectation is assumed to be independent of the right ascension. The FC and PC topologies extend to all declinations and have a slightly positive slope due to oscillations in the upward-going neutrinos. The two peaks are due to the atmospheric neutrinos coming from near the horizon. Here, the cosmic rays are more likely to interact due to the fact that the atmosphere is thicker and that path length for traversing this region is longer and so there is a greater chance for the cosmic ray to decay. The UPMU topology requires that the neutrino events come from below the horizon, and thus there are no events where the reconstructed direction has declinations above 54 °. Neutrinos coming from declinations of greater than -54° spend increasingly more time above the horizon, and so there is a decreasing trend above this declination. The maximum number of UPMUs are at -54°. This is because these neutrinos are near, but always below the horizon, where a greater flux of atmospheric neutrinos is expected.

We then used the SK data to calculate the number of detected events (N) in the search cone for each of the IceCube search directions. Figure 2 shows the number of detected neutrino events in the search cone compared with the background expectation.

To determine if there were any statistically significant excesses in our data, we calculated the test statistic, Λ, for each search direction using Equation 2. The expected distribution of Λ was also calculated using the 500-year simulated MC data set. The UPMU topology was used and the declination of -31.2° was assumed. The events were first randomly assigned a right ascension assuming a flat local sidereal time. The number of events in a 5° search cone was then determined, scaled for the appropriate livetime. This was compared to the background expectation N_B for this declination and Λ was calculated using Equation 2. This algorithm was repeated 1×10^7 times, randomly assigning new right ascension values to the data each time. The expected distributions for the different topologies, as well as the different declinations, were checked and found to be the same.

Figure 3 shows the test statistic for all three topologies for each search direction. Λ was found to be zero most often, signifying that the number of events in the search cone best fit to the expected background, or that there were fewer

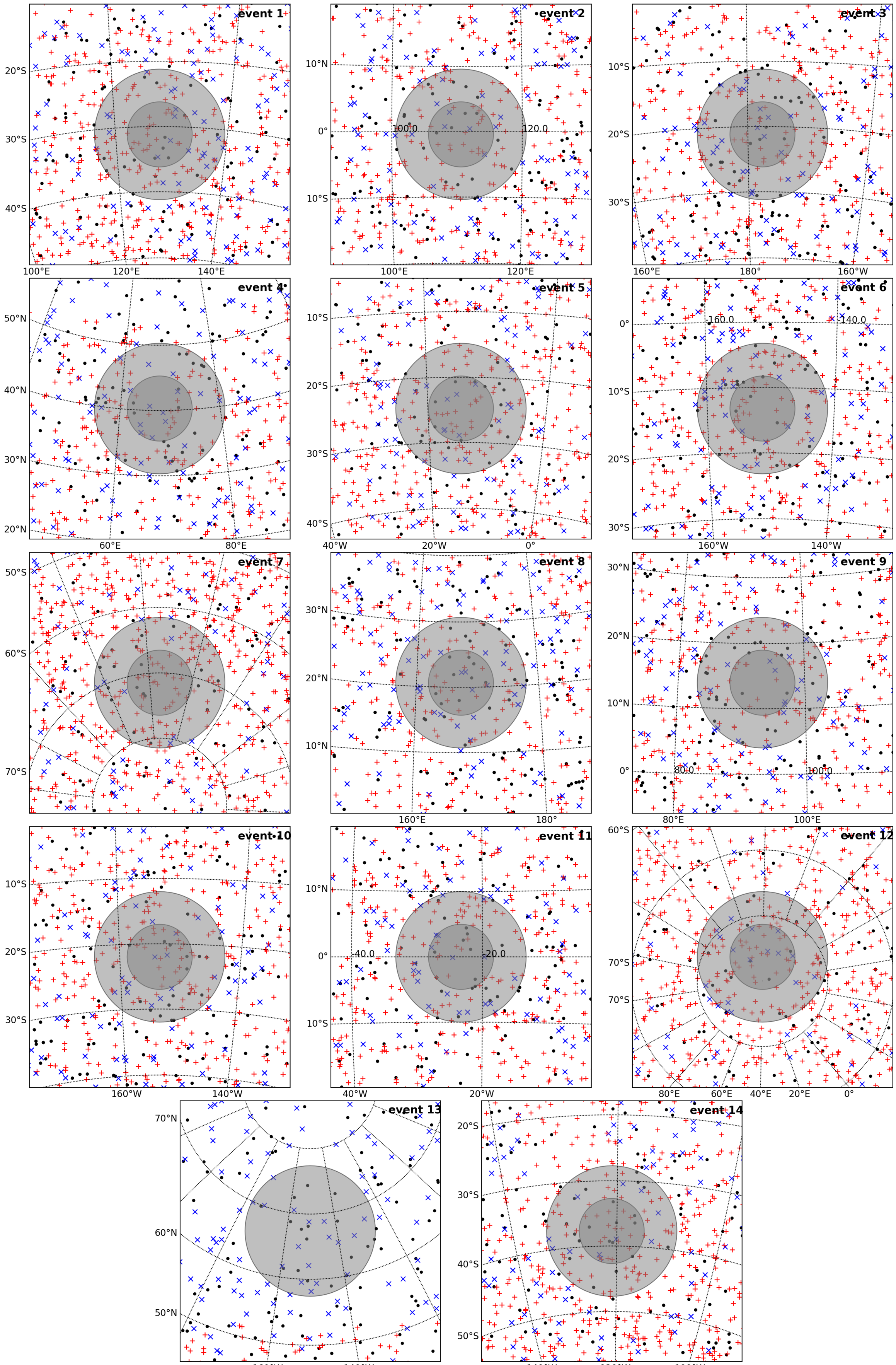

Figure 1. The detected FC (black circle), PC (blue x) and UPMU (red +) events in and around the search window. The position of events are shown in equatorial coordinates with right ascension on the x-axis and declination on the y-axis. The dark grey disk shows the 5 degree search cone used for UPMU events, while the light grey disk shows the 10 degree search cone used for FC and PC events.

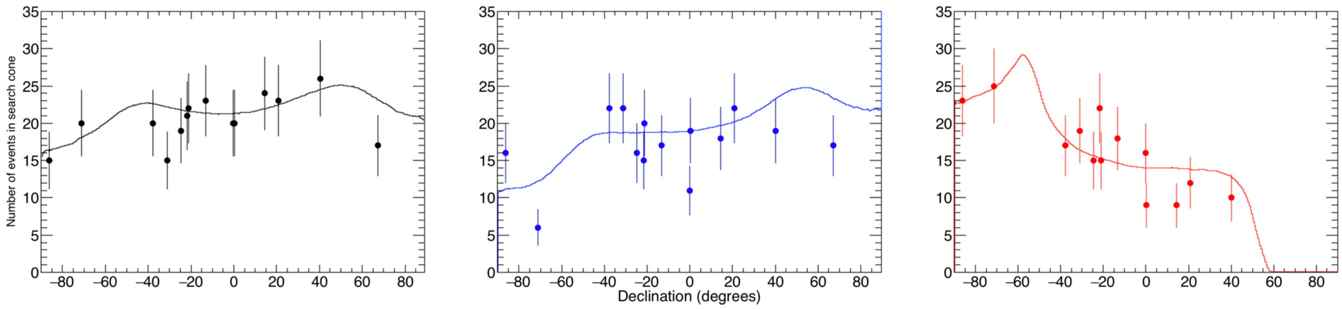

Figure 2. The number of events expected in the search cone (solid line) for FC (black, left), PC (blue, center), and UPMU (red, right) topologies, shown with the number of events found in the search cone from the data (points). The errors shown here are $\sqrt{N}$. Event 13 (declination of 67.4°) was not visible to the UPMU data set since it is always above the horizon in the SK detector.

events in the search cone than the expected background would suggest. No excess of greater than 2σ was found for any of the topologies in any of the search directions. No search direction jointly yielded a significantly higher Λ in all three of the topologies.

The most significant event had a calculated Λ of 1.1, which corresponds to a significance of about 1.1 σ from the MC background prediction. This was in the UPMU data sample in the direction of event number 10, corresponding to a declination of -22°. In this search direction, we observed 22 events and expected 13.7 events from the atmospheric background MC prediction.

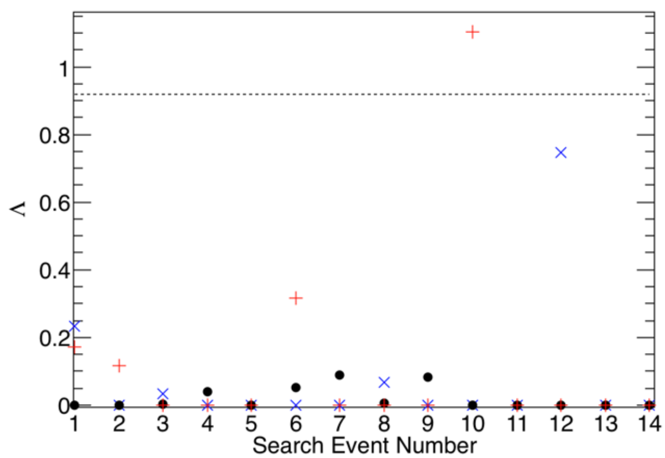

Figure 3. The test statistic for each search direction, plotted for the FC (black circle), PC (blue x), and UPMU (red +) topologies. The dashed line represents the 1 σ expectation calculated from the atmospheric MC. No trend can be seen for an excess in a particular search direction.

Figure 4 shows the distribution of the test statistic separately for each of the three topologies considered, along with the expected test statistic distribution calculated using simulated data from our Monte Carlo code. As seen here, no statistically significant excesses are seen and the distribution of the test statistic from the data matches the background expectation. The confidence levels are determined using the MC test statistic distribution by calculating the Λ where 68.3%, 95.4%, and 99.7% of the test statistic prediction is enclosed for 1 σ, 2 σ, and 3 σ, respectively.

4.1. *Searching for a coincidence with the IceCube multiplet event*

In addition to the search for excesses in the direction of the IceCube track events, we separately searched for coincidence events with the IceCube multiplet event reported in Aartsen et al. (2017). On February 17, 2016, IceCube observed three neutrino candidate events within less than 100s separated by 3.6°. This type of multiplet event would be expected to occur once every 13.7 years. No optical counterparts were found in the follow up searches discussed in Aartsen et al. (2017).

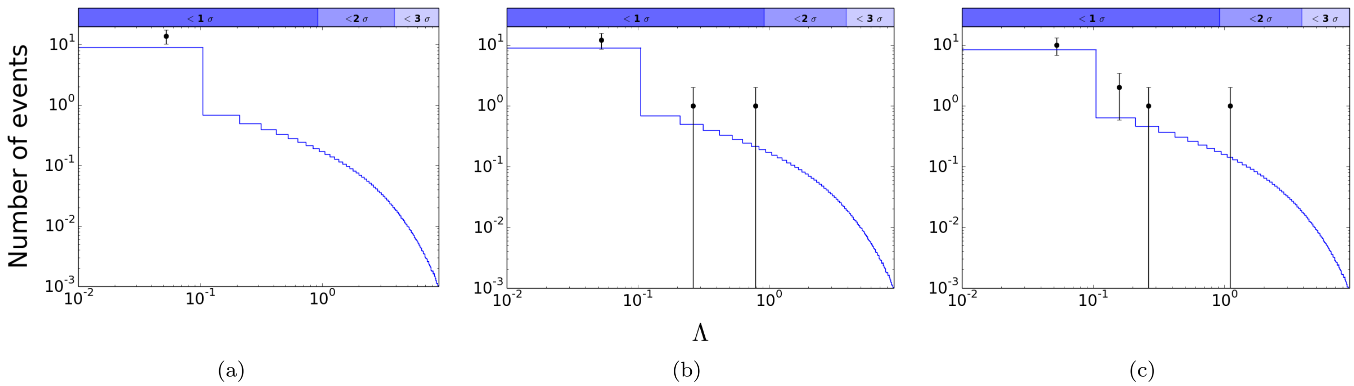

Figure 4. The binned Λ values obtained for each of the 14 (13 for UPMUs) search directions for (a) FC, (b) PC, and (c) UPMU topologies. Also shown is the expected test statistic distribution as predicted from our MC simulation. The confidence levels are determined by enclosing 68.3 %, 95.4 %, and 99.7% of the test statistic prediction for 1 σ (dark blue), 2 σ (medium blue), and 3 σ (light blue), respectively.

In SK, we searched for neutrino candidate events in the FC, PC, and UPMU data sets in a 500-s time window around the time of the first detected neutrino in the multiplet event. No SK candidate events were detected in any of the three topologies.

We also performed a spatial coincidence search over all SK phases using the same method used for the IceCube track events reported in the other sections of this paper. In the direction of the triplet event (dec = 39.5°, RA = 26.1°), we detected (expected) 24 (24.5) FC events, 26 (23.2) PC events, and 16 (12.9) UPMU events. The likelihood ratio (Λ) for the three topologies was calculated to be 0 for FC, 0.14 for PC, and 0.30 for UPMU, which is all less than the one sigma value determined using the atmospheric MC background.

5. CONCLUSIONS

We performed a search for SK neutrino detections coincident in direction with the IceCube track events. Using Poisson statistics, we used SK data taken from April 1996 - April 2016 to determine if there was any excess of events in each of the search directions. The detected numbers of SK neutrino events in each of the search directions were consistent with the background expectations. The most significant Λ was 1.1 at a declination of -22° in the UPMU data set, which corresponds to a significance of about 1.1 σ using the atmospheric MC prediction.

We also looked for coincidence events with the IceCube multiplet event reported in (Aartsen et al. 2017). In the time coincidence search, no events were found within a ± 500 s time window from the first detected IceCube event. In the direction coincidence search, the number of events detected over the lifetime of SK from the direction of the IceCube multiplet event was consistent with atmospheric background for the FC, PC, and UPMU topologies.

These results represent the first search for coincident neutrinos with IceCube events that has been extended down to the few GeV energy regime. Given the unknown origin of these astrophysical neutrinos, it is worth exploring all available data in the hopes of a new discovery. This search was not optimized for a particular energy spectrum, which trades improved sensitivity to the popular energy spectra (E^{-2}, for example) for the flexibility of being model independent. This search is useful for constraining the behaviour of astrophysical neutrinos in the lower energy regime and guiding new models which predict neutrino behaviours at lower energies.

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